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The Her X-1 Spectrum: A Measure of the Field Near the Magnetic Poles of A Neutron Star

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Summary

The steep high energy cutoff observed in the spectrum for Her X-1 is analyzed in terms of the severely modified Thomson scattering that dominates the radiative transfer in a highly magnetized plasma near the surface of a neutron star. The data are shown to indicate a field of about 10^{13}G near the magnetic poles and the stopping of accreting matter by nuclear collisions in the neighboring plasma.

Key words: Her X-1, neutron star, Thomson scattering

1. Introduction

Basko and Sunyaev (1974) and Tsuruta (1974) have described how the beaming of X-radiation necessary to explain the Her X-1 pulsar could arise from the anisotropy in scattering of photons from a highly magnetized plasma. In this communication, we show that the energy dependence of such scattering could also induce a spectral distortion adequate to explain the remarkably sharp high energy cut-off (at $\sim$ 24 keV) in the Her X-1 pulsar spectrum previously reported by us (Holt, Boldt, Rothschild and Serlemitsos, 1974).

2. Model

In the model of Basko and Sunyaev the magnetic field funnels the accreting matter towards the magnetic poles where free-fall to the surface

is stopped mainly via nuclear collisions (i.e. Coulomb collisions in a highly magnetized plasma are considered to be negligible). The radiative transfer of the X-rays produced within this optically thick atmosphere is dominated by Thomson scattering. As recently demonstrated (Canuto et al., 1971; Lodenquai et al., 1974), the Thomson scattering cross-section in a magnetized plasma (σ_H) is expected to deviate drastically from the field-free cross-section (σ_o). If θ is the angle between the magnetic field (H) and the wave vector of incident electromagnetic wave, we have, as $\theta \to 0$,

$$(\sigma_H^{\pm}/\sigma_o)_{E,\theta} \approx [E/(E_H \pm E)]^2 + \tfrac{1}{2}\sin^2\theta \quad (1)$$

where (+) and (-) refer to the ordinary and extraordinary modes of propagation respectively, E is the photon energy and E_H is the cyclotron energy defined as

$$E_H = (h/2\pi)\ (e/mc)\ H. \quad (2)$$

The important feature of Eq. (1) for this discussion is that, for $E \ll E_H$, Thomson scattering along the field is much less than expected from the field-free cross-section. Therefore, we pursue the suggestion that an unscattered pencil beam may indeed emerge from well within the optically thick atmosphere near the poles.

Following Basko and Sunyaev, we consider the situation where the rate of energy release by accretion varies in the atmosphere as $\exp(-\tau/\tau_o)$, where τ is the optical depth measured with respect to the field-free Thomson scattering cross-section and τ_o is that particular value of τ corresponding to a nuclear mean free path. With a cosmic abundance of elements $\tau_o \approx 10$, whereas for iron $\tau_o \approx 20$.

Since the source energy spectrum is expected to be essentially constant up to about 30 keV for photons Comptonized in the plasma near the magnetic poles of Her X-1 (Basko and Sunyaev, 1974), the spectral structure of the emerging unscattered beam will be determined mainly by the energy dependence of the modified Thomson scattering that removes photons from this beam. A good approximation to the spectrum of the unscattered radiation should thereby be obtained as follows:

$$dS/dE \propto (\tau_o)^{-1} \int_o^\infty \exp[-(\tau/\tau_o) - \tau(\sigma_H/\sigma_o)_E] d\tau = [1 + \tau_o(\sigma_H/\sigma_o)_E]^{-1} \qquad (3)$$

where S is energy flux and $(\sigma_H/\sigma_o)_E$ is obtained from Eq. (1), neglecting $\sin^2\theta$.

3. Results and Discussion

In making comparisons of Eq. (3) with our spectral data, we have found that $\tau_o = 10$ and $E_H = 100$ keV (i.e. $H \approx 10^{13}$G) give results that are adequate for obtaining the behavior characteristic of this effect. The two curves shown in Figure 1, superposed upon the spectral data, correspond to

$$(dN/dE)_{\pm} = (0.15/E)\{1+10[E/(100 \pm E)]^2\}^{-1} \ (\text{cm}^2 \sec \text{keV})^{-1} \qquad (4)$$

where (+) and (-) again refer to the ordinary and extraordinary modes, respectively. As analyzed by Basko and Sunyaev, the ratio of intensity in the extraordinary mode to that in the ordinary mode is expected to increase with photon energy, being comparable at about 10 keV for the case considered here. The data exhibited in Figure (1) show that this behavior may be applicable to the Her X-1 spectrum. The apparent importance of the extraordinary mode at energies higher than about 10 keV indicated by these data might also account for the change in pulse profile

(Holt, Boldt, Rothschild and Serlemitsos, 1974) that sets in for this same energy band. Temporal variations in pulse profile remain to be explained.

To check the sensitivity of the pronounced spectral effect exhibited here with respect to the distribution in τ assumed for the source function, we have also considered an extreme situation where the source resides exclusively at the optical depth τ_o. The curves corresponding to this are shown in Figure (2), superposed upon the same data as shown in Fig. (1). The expression used for this computation is

$$(dN/dE)_{\pm} = (0.15/E) \exp\{-\tau_o[E/(E_H \pm E)]^2\} \qquad (5)$$

where the curves shown in Fig. (2) were evaluated for $\tau_o = 10$ and $E_H = 120$ keV. The results obtained for this case are qualitatively the same as those obtained for the distributed source model used for Eq. (4). We conclude that the spectrum of the emerging unscattered beam depends mainly upon τ_o and E_H, and that the detailed structure of the source with respect to τ plays a minor role. Hence, the spectral shape we observed for Her X-1 is likely to be a feature inherent to the underlying neutron star (i.e. determined by the surface magnetic field strength and nuclear collision length near the magnetic poles), rather than being a direct indicator of the accretion process itself. Specifically, we infer that the magnetic field at the poles is about 10^{13} G and that the nuclear collisions in the nearby plasma are probably not dominated by iron.

Since Thomson scattering in a magnetized plasma appears to severely surpress the spectrum of the Her X-1 pulsar emission at $E \gtrsim 24$ keV, we expect that any X-radiation at higher energies might not be pulsed. A balloon-borne experiment for observing hard X-rays from Her X-1 (Iyengar et al.,

1974) gives an upper limit of 10% for the pulsating component in the bandwidth 20-45 keV whereas our observation at the lower energies considered here indicates that most of the emission is from the pulsar.

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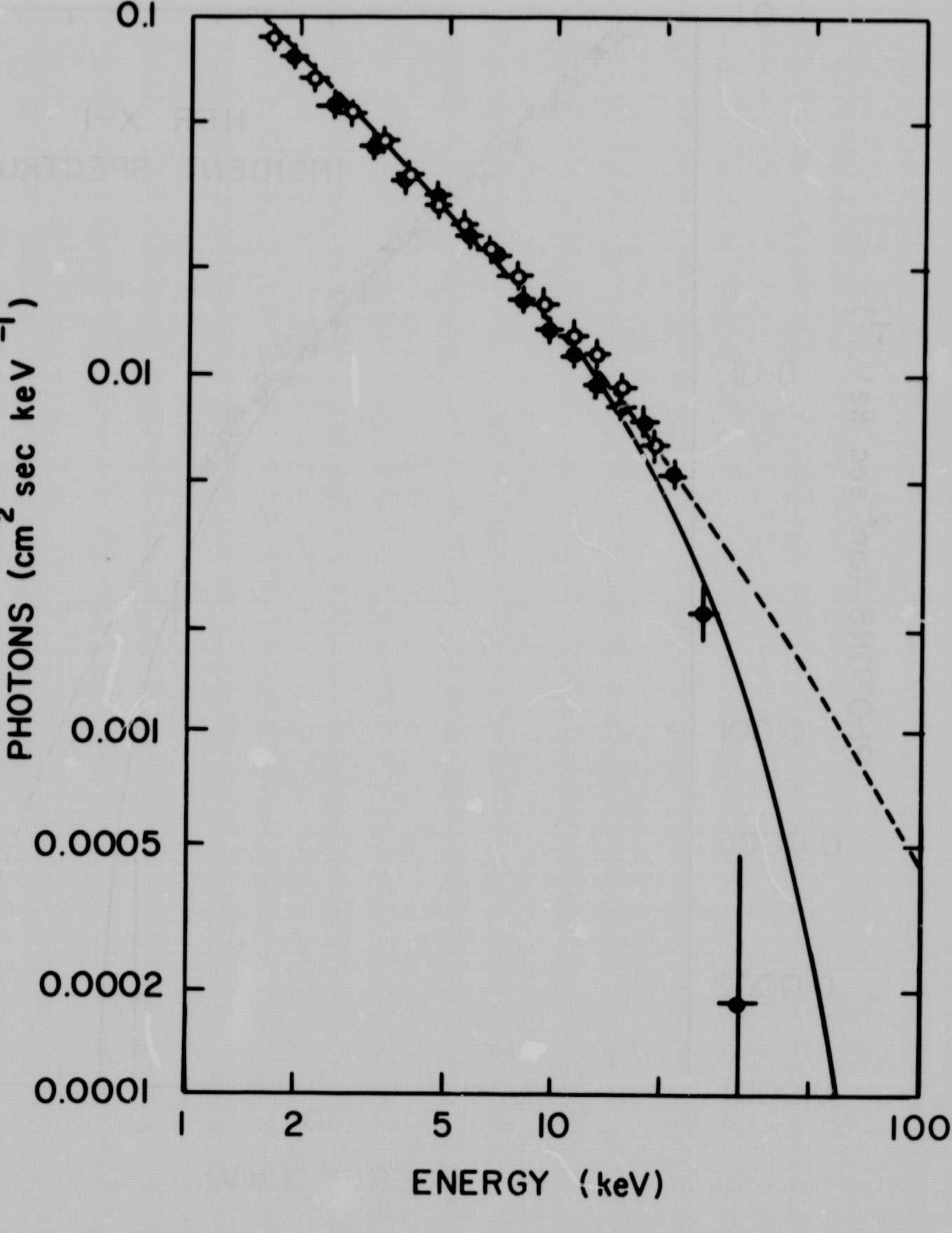
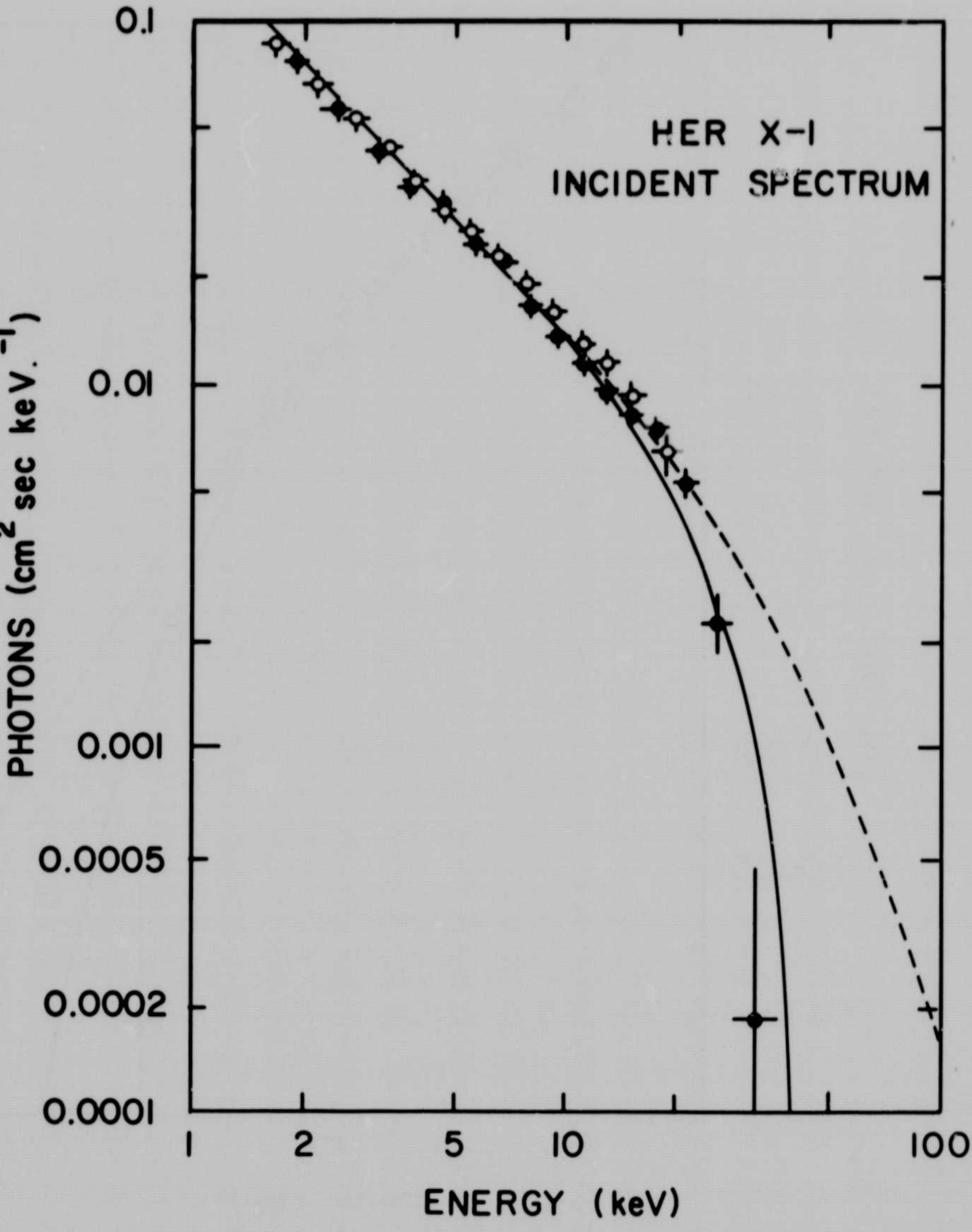
Fig. 1 The Her X-1 spectrum obtained 4 October 1973 (at binary phase 0.6 referenced to eclipse center). The open symbols refer to data from an argon-filled counter, and the closed symbols refer to data from a xenon-filled counter (same experiment; see text). The dashed and solid curves were obtained from Eq. (4) for the ordinary and extraordinary modes, respectively.

Fig. 2 The same spectral data as in Fig. 1. The dashed and solid curves were obtained from Eq. (5) for the ordinary and extraordinary modes, respectively, with $\tau_o = 10$ and $E_H = 120$ keV.


0.1
0.01
0.001
0.0005
0.0002
0.0001
PHOTONS (cm^2 sec keV^{-1})
1
2
5
10
100
ENERGY (keV)


HER X-1
INCIDENT SPECTRUM
PHOTONS (cm^2 sec keV.$^{-1}$)
ENERGY (keV)
0.1
0.01
0.001
0.0005
0.0002
0.0001
1
2
5
10
100